INFORMING WELL-BALANCED DAYLIGHT DESIGN USING LIGHTSOLVE

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ABSTRACT

Designing spaces that are able to balance illumination, glare and solar gains over a whole year is a real challenge, yet a problem faced every day by building envelope designers. To assist them in this search, a full year, climate-based daylighting simulation method was developed, called Lightsolve, meant to be used early on in the design process when façade and space details have not yet been defined. It focuses on the variation of daylight performance over the day and the year, combining temporal performance visualization with spatial renderings, and including an expert system to support a guided search process.

This paper describes the foundations and set of innovative simulation resources that Lightsolve offers as a whole, and puts its different components - including a time reduction method, a set of three goal-based metrics and an expert system - back to Lightsolve's overall context aiming to an early stage, comprehensive, prospective support for daylighting design.

INTRODUCTION

Daylighting design is both highly relevant to cutting edge societal issues such as energy conservation, sustainability and health, and highly sensitive to careful planning and control. With lighting being responsible for the greatest energy requirements in commercial buildings [1] - that are also mostly used during daytime -, and with heating and cooling being the two second most energy-demanding building functions [2], it appears very clearly how efficient daylighting and solar control strategies can have a tremendous impact on energy use. Savings predictions for lighting can vary between 20% and 80% [3,4]; but these savings can only be effective if one also carefully accounts for our visual needs and our comfort and health criteria. The main challenge resides in the reconciliation of the many factors influencing how daylight and sunlight each interact with the built environment and in the great variations they show in intensity and distribution depending on location, weather and time.

If one wants to propose new methods to inform designers about daylighting management, these methods have to be developed in harmony with the way architects work and think. Today, simulation tools have become the dominant form of design support [5,6] but due to the large number of parameters involved and the need for detailed, climate-based analyses to be realistic about daylighting potential [7,8], evaluating annual daylighting performance of a schematic building project interactively and comprehensively is particularly challenging.

An innovative simulation project called Lightsolve has been initiated to address this challenge, that intends to inform the design process through a goal-driven, interactive guided search process. It is based on expert rules, and on combining an inverse (goal-based) approach with a simultaneous visualization of quantitative and qualitative aspects of space and of its annual, climate-based performance.

LIGHTSOLVE OVERALL CONCEPT

Lightsolve aims to provide building designers with the means necessary to assess critical parameters of a successful daylighting design by efficiently combining qualitative and quantitative criteria in the search process. The question of daylighting metrics has become a key design issue to solve in today's environmental context: what kind of metrics would be appropriate to provide a comprehensive yet condensed assessment of the daylighting performance of a space? The challenge is to approach this problem both from quantitative and qualitative perspectives, while still conveying enough information about the variability of daylight over time and space, and its dependence on location and climate. With so many parameters involved, it is essential to gauge the extent to which these metrics will still be able to inform design.

The general approach for Lightsolve is to inform well-balanced daylight design during early design stages through an interactive visualization and a pro-active, guided improvement of full-year time-varied daylighting performance [9]. One of the underlying principles in terms of how daylighting performance is evaluated is to make it specific to the user's own performance objectives and to his or her areas of interest, as well as to combine a synthetic perspective of full-year data with a visual impression of what the space looks like over time.

The metrics used in Lightsolve differ from most existing daylighting simulation programs in two ways: they are goal-based and they place emphasis on the variation of daylight performance over the day and the year. The temporal map [10] indeed appears as a form of graphical representation of performance that is particularly well suited to schematic design stages because it is able to inform designers at a glance about how a given metric of interest varies over time, daily and annually. The days/months of the year are plotted along the horizontal axis, and the times of day are plotted along the vertical axis (see Figure 1(b)).

In the Lightsolve framework, we use that representation to show how closely the users' current design fulfills their own (or standard-based) visual comfort, solar gain and light distribution goals, on an annual yet time-varied basis that accounts for weather conditions [11]. An intuitive color scale (Figure 1(a)) indicates how closely the goals are met over the year: yellow indicates that the goals were met for this sensor (or that solar gains are neither excessive nor insufficient), red indicates that values were too high, and blue that they were too low. The three Lightsolve metrics express the performance of each *entire* area of interest (big or small, defined by the user) rather than on a point per point basis, as discussed below.

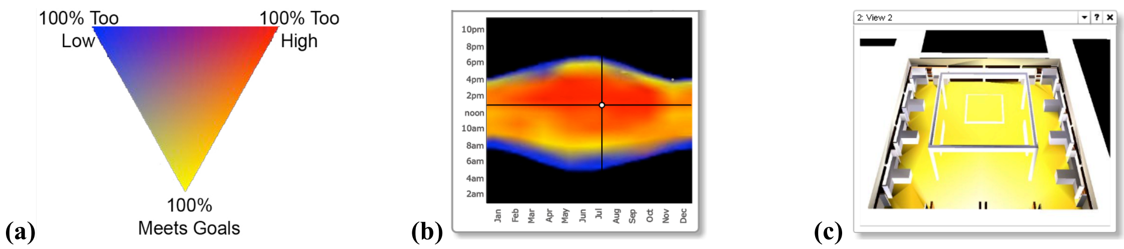

Figure 1: Reading Lightsolve Temporal Maps – (a) Color scale (b) Correlation of time/day with performance (color) and (c) with lighting distribution (renderings).

Year-representative series of renderings are also produced and associated to a given time of day/year and weather condition (the dominant one e.g., Fig 1(c)). In the Lightsolve interface (Figure 2(a)), these renderings (right + 2(b)) are interactively displayed together with sky type occurrence (2(a) upper left) as one moves a cursor over the temporal map (middle), and are combined with the goal-based visualizations of annual performance (temporal maps) for illumination (based on desired illuminance ranges), glare (based on desired glare tolerances) and solar gains (based on probable heating/cooling needs), whose basis is detailed below.

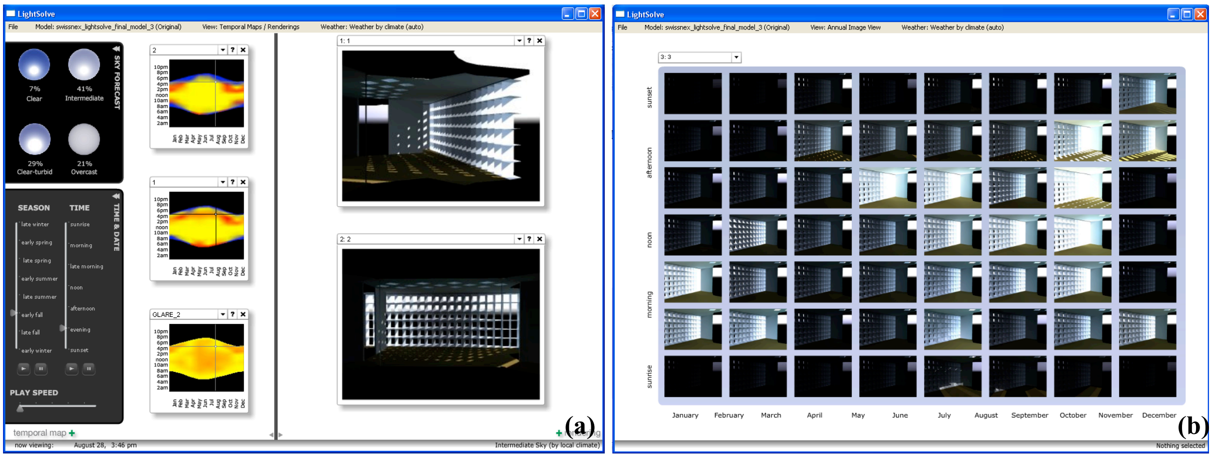

Figure 2: Lightsolve analysis interface – (a) Time-varied display of performance interactively linked to renderings of the space (b) Annual Image Map showing all renderings over time.

One of Lightsolve's major innovations also resides in its user-interactive expert system approach. The expert system allows designers to create a 3d model of their own design and to input project-specific performance goals for illuminance and glare within the space; it aims at providing performance-based decision support while respecting the role of the architect and his or her design intent and is described in further detail below.

FULL-YEAR, TIME-VARIED ANALYSIS

To allow for climate-specific calculations, illuminance and glare values are calculated for each sensor plane patch and for each of four sky types [12], ranging from overcast to clear. A climate-based representative value is then calculated as a weighted average from each sky type based on their respective occurrence during that time period. To make whole-year calculations more efficient, the year is split into 56 periods and climate-based data are calculated for each of them as far as the diffuse component of daylight is concerned [9]. The comparisons between temporal maps produced using the data reduction method and those produced using detailed illuminance data extracted from the program Daysim at 5 minute intervals showed a strong visual and numerical correlation [13], illustrated in the example shown on Figure 3. A separate calculation for zero-bounce direct sunlight is performed for 1200 sun positions (80 times of year and 15 times of day) and results are combined to the first (diffuse) set [14].

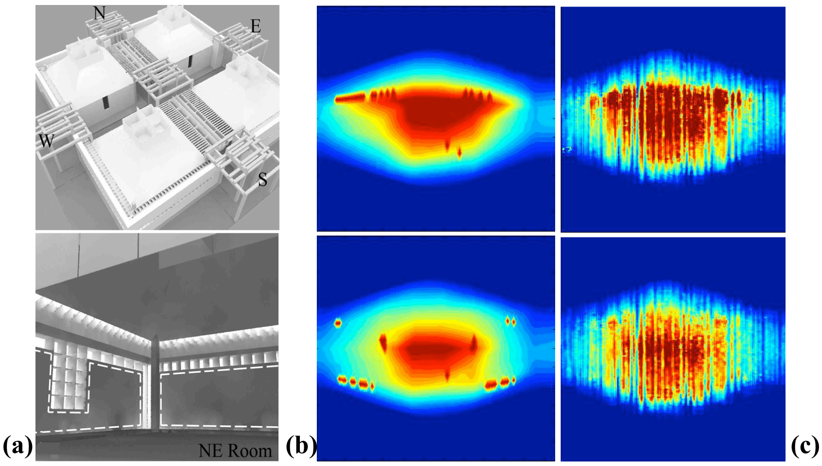

Figure 3: Condensing annual data. Museum case study (a) used to compare the 56 time period reduction method with sun overlay (b) against Daysim (shadow casting mode) (c).

Rendering and Calculation Engine

The overall intent of Lightsolve being to inform design in an exploratory way, there was a need for a quick calculation engine that could produce both numerical results (at the basis of temporal maps) and renderings over a whole year so that interactivity could be maintained. A hybrid global illumination method was developed for this purpose at the Rensselaer Polytechnic Institute, called the LightSolve Viewer or LSV [15]. It relies on patch-based radiosity for the sky and uses indirect illumination and shadow volumes for pixel-based shadows for direct illumination by the sun. This rendering system was validated through a set of qualitative and quantitative comparisons with Radiance and a pixel difference of less than 10% was found between LSV and Radiance for a variety of different scenes, camera positions, and daylighting conditions [15].

Goal-Based Metrics

Unlike most daylighting analysis tools, the three metrics that were developed for Lightsolve and are represented as colored temporal maps emphasize the time-variation of light over its detailed spatial distribution. They are also explicitly goal-based: performance objectives in daylighting can indeed vary greatly depending on the type of space and the intentions of the designer. A set of three metrics, whose underlying principles are illustrated in Figure 4, were developed to display goal-based performance information for a user-defined area of interest on a single temporal map and to offer a comprehensive and intuitive way to represent annual daylight performance of a design proposal; details can be found in [11]. A color scale - consistent amongst the three metrics - indicates how closely the goals are met over the year.

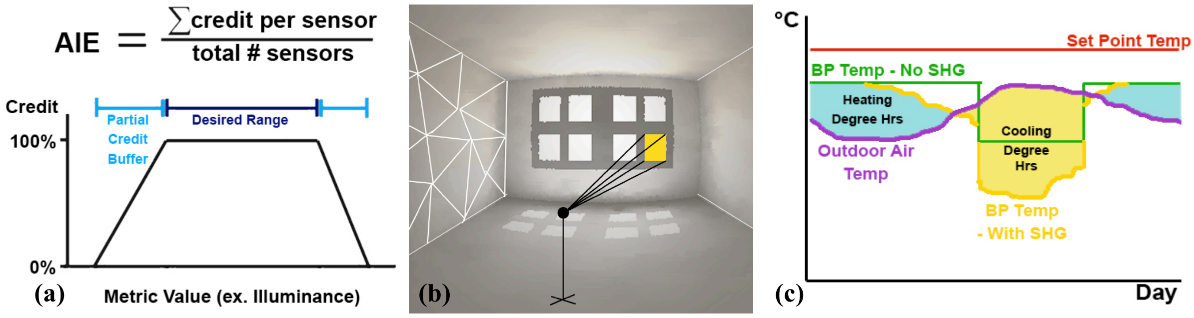

Figure 4: Lightsolve Metrics – (a) Acceptable Illuminance Extent (AIE) credit system (b) Glare Avoidance Extent (GAE) derived from DGP and based on window luminance and radiosity model (c) Solar Heat Surplus/Scarcity (SHS) based on cooling/heating daily totals.

Illumination

The illumination metric, called Acceptable Illuminance Extent (AIE), calculates how the portion of a user-defined area of interest in which the illuminance stays within a chosen range varies over time. In other words, this metric condenses the portion of a user-defined area of interest in which the illuminance stays within a chosen range to a single percent, and displays the variation of that percent over time. It assigns full credit to sensor portions within range, and partial credit to sensor portions out of range but within a user-defined ‘buffer’ interval. It is referred to as Acceptable Illuminance Extent (AIE), as shown in Figure 4(a).

Glare perception

Similarly, a single number representative of overall glare perception within an area of interest is introduced as Glare Avoidance Extent (GAE) and based on the Daylight Glare Probability (DGP) metric. The derived GAE metric used in Lightsolve indicates the proportion of the glare zone or glare sensor area that falls above the glare threshold considered non-acceptable by the user. It can therefore represent the glare risk for a particular location and a particular viewpoint over the year (small unique glare sensor with its normal facing that direction) but can just as well indicate the overall glare risks for a space or a range of viewing locations (e.g. for all the students in a classroom). Because this glare analysis is run annually and often for multiple viewpoints, it required more efficient methods for computing glare, that were developed for that purpose and are schematically illustrated in Figure 4(b) [16]. It relies on threshold values suggested by the DGP author for glare tolerance.

Solar gains

Finally, a new solar gains metric called Solar Heat Scarcity/Surplus (SHS) is used to convey the urgency of either allowing more direct solar gain or avoiding it, based on revisited balance point calculations [17] (see Fig 4(c)). Although dynamic energy analyses should ultimately be used in determining energy loads, balance point can be as useful indicator in the earliest stages of design. The recently released 16 DOE Benchmark Commercial Buildings [18] was used to validate this approach. Within the Lightsolve environment, the Solar Heat Scarcity and Surplus metric requires additional input about the thermal properties of the envelope and building type and occupancy but is able to provide a good approximation of how much of a liability or benefit the daylight-associated solar gains are for the proposed designs.

Although the non-spatial aspect of solar heat gain usually makes it more difficult to analyze along side illuminance or glare, the value of resorting to time-variant graphics was made evident from its ability to provide a basis of comparison so that solar heat gain information can be comparable with location-based data.

EXPERT SYSTEM

The expert system consists of two major components: a daylighting knowledge-base which contains information regarding the effects of a variety of design conditions on resultant daylighting performance [19], and a fuzzy rule-based decision-making logic which is used to determine those design changes most likely to improve performance for a given design [20]. As in Lightsolve's analysis mode, the user starts with an initial design, and be guided towards improved performance like by a "virtual daylighting consultant. By involving the designer and utilizing his or her knowledge as well as the intelligence built-in the tool, the process is made more efficient while the exploration space is expanded.

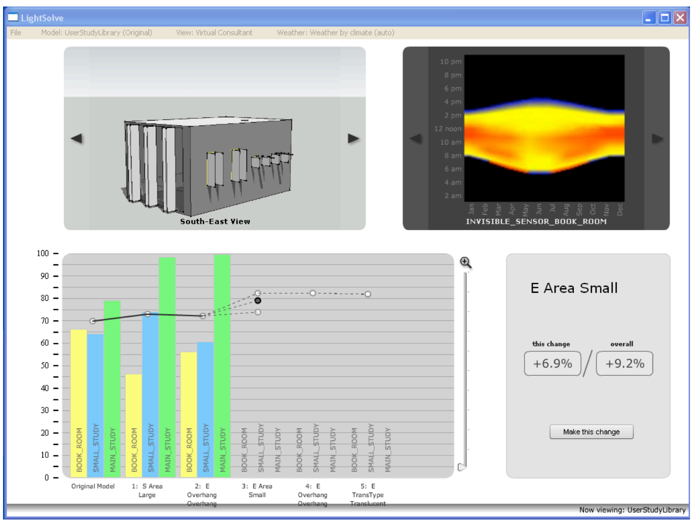

Figure 5: Lightsolve Expert System interface (Virtual Consultant) – Guided search to increase annual performance for all areas of interest and all and all performance objectives.

The expert system is currently implemented in Google SketchUp as a plug-in; its user interface, illustrated in Figure 5, displays the current performance of a given design and the list of design changes suggested to the user. The tool was evaluated against high performing benchmark designs generated with a genetic algorithm [21] and tested for varying levels of aesthetic constraints. The results of these studies indicated that the expert system was successful at finding designs with improved performance for a variety of initial geometries and daylighting performance goals [20]. It has also been tested by a group of designers who were asked to complete a design task with the system and to evaluate their experiences using the tool. These studies demonstrated a good acceptance by designers and demonstrated its ability to effectively guide a design process while offering an educational potential [22].

CONCLUSION

This paper discusses the underlying principles of the different components of a new approach in daylighting simulation named Lightsolve. The main innovations are pointed out, and brought together in a more holistic overview of the project. Lightsolve shows promise as a complementary method to daylighting performance evaluation: instead of summarizing time and emphasizing spatial light distribution, Lightsolve offers a way to evaluate broader areas within a space with an emphasis on how this performance varies over the seasons and time of day. This perspective thus seems particularly relevant to early design stages. The positive feedback received during the expert system user study [22] encourages the authors to pursue this development effort into a tool that could be used more broadly. Such resources could indeed enable a desirable shift in schematic stage design practices and move daylighting analysis one step closer to achieving “best practice” recognition.

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REFERENCES

1. Swiss Federal Office of Energy : Energieforschung 2009 – Ueberblicksberichte. Swiss Confederation, 2009.
2. US Deptartment of Energy: "Buildings Energy Data Book" (September 2007), sec. 1.3.3.
3. Bodart M., De Herde A. : Global energy savings in offices buildings by the use of daylighting. Energy & Buildgs 34(5), 421-429, 2002.
4. Ihm P., Nemri A., Krarti M.: Estimation of lighting energy savings from daylighting. Buildg and Envment 44 (3), pp. 509–514, 2009.
5. Reinhart C, Fitz A.: Findings from a survey on the current use of daylight simulations in building design. En.&Bldgs 38(7), 824-835, 2006.
6. Sarawgi T. : Survey on the use of lighting design software in architecture and interior design undergraduate education. International Journal of Architectural Computing 4(4): pp. 91-108, 2006.
7. Reinhart, C.F., Wienold, J.: The Daylighting Dashboard - A Simulation-Based Design Analysis for Daylit Spaces, Building and Environment, 46(2), pp. 386-396, 2011.
8. Mardaljevic, J., Heschong, L., Lee, E.: Daylight metrics and energy savings, Lighting Res. and Technology, 41(3), pp. 261-283, 2009.
9. Andersen, M., Kleindienst, S., Yi, L., Lee, J., Bodart, M., Cutler, B.: An intuitive daylighting performance analysis and optimization approach, Building Research and Information, 36 (6), pp. 593–607, 2008.
10. Mardaljevic, J.: Spatio-temporal dynamics of solar shading for a parametrically defined roof system, Energy & Bldg 36, 815-823, 2004.
11. Kleindienst, S., Andersen, M.: Comprehensive Annual Daylight Performance from Goal-Based Design Inputs, Bldg Res.&Inf, submitted
12. Perez R, Michalsky J, Seals R.: Modelling Sky Luminance Angular distribution for real sky conditions; Experimental evaluation of existing algorithms, Journal of the IES, 21(2), pp. 84-92, 1992.
13. Kleindienst, S., Bodart, M., Andersen, M.: Graphical Representation of Climate-Based Daylight Performance to Support Architectural Design, LEUKOS, 5(1), pp. 39-61, 2008.
14. Kleindienst, S.: Time-Varied Daylighting Performance to Enable a Goal-Driven Design Process, PhD thesis, MIT, 2010.
15. Cutler, B., Martin, S., Sheng, Y., Glaser, D., Andersen, M.: Interactive Selection of Optimal Fenestration Materials for Schematic Architectural Daylighting Design, Autom. in Construction, 17(7), 809-823, 2008.
16. Kleindienst, S., Andersen, M.: The Adaptation of Daylight Glare Probability to Dynamic Metrics in a Computational Setting, In Proceedings of Lux Europa 2009, Istanbul, September 9-11, 2009.
17. Kleindienst, S., Andersen, M.: Solar Heat Surplus and Solar Heat Scarcity: the Inclusion of Solar Heat Gain in a Dynamic and Holistic Daylight Analysis, Proc. IBPSA-USA SimBuild 2010, New York, August 2010.
18. Torcellini P., Deru M., Crawley D.B. et al.: DOE Commercial Building Benchmark Models, Proc. 2008 ACEEE Summer Study, 2009.
19. Gagne, J.L., Andersen, M.: A daylighting knowledge-base for performance-driven facade design exploration, accepted, LEUKOS.
20. Gagne, J.L., Andersen, M., Norford, L.K.: An Interactive Expert System for Daylighting Design Exploration, Bldg & Env, in press.
21. Gagne, J.L., Andersen, M.: A Generative Façade Design Method Based on Daylighting Performance Goals, J. Bldg Perf. Sim., in press.
22. Jaime L. Gagne, An Interactive Performance-Based Expert System for Daylighting in Architectural Design, PhD thesis, MIT, 2011.